A LASER TRACKING DYNAMIC ROBOT METROLOGY INSTRUMENT

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Abstract

Research work over several years has resulted in the development of a laser tracking instrument capable of dynamic 3D measurements of robot end-effector trajectories. We describe the instrument characteristics and experiments to measure the static and dynamic performance of a robot in an industrial manufacturing environment. We speculate on the use of this technology for space applications.

1. Introduction

Robots developed for space applications are likely to be significantly different from their earth-bound counterparts. Structural weight will be as low as possible, consistent with adequate stiffness, with arms designed for a wide variety of working volumes. At one extreme we have loading/unloading arms for use with the space shuttle and at the other we have delicate, miniature arms for small-scale space laboratory experiments. In addition, the dynamic speed requirements of space robots are likely to remain much lower than industrial robots to cope with inertia re-action problems.

To achieve overall improvements in such robots the designer will address himself to such characteristics as machine structure, drive characteristics, adaptive control of the servomechanism for each articulation, software limitations, and so on. All of these areas to a greater or lesser extent require sophisticated measurement techniques to validate the design approach and provide insight into the deficiencies of present robots. A particularly good example of this is the significant variation in the dynamic characteristics of most robots within the working volume as a result of both load and positional changes. Good instrumentation is vital to achieve an accurate experimental description of robots under these conditions.

Many different non-contacting techniques have been investigated for 3D dynamic metrology related to robot technology [1-10]. Of these, the three most promising approaches for industrial applications are the camera based lateral effect photodetector [5], the laser interferometer [10] and the laser triangulation tracking system [9]. For space applications, the latter method has particular attractions due to its large static and dynamic measurement range together with its robust measurement and control aspects. The next section describes the characteristics of an instrument developed at Surrey University based on tracking laser triangulation principles.

2. The Laser Tracking Instrument Concept

The measurement instrument is based on a two-dimension measuring unit or sub-system which can be combined with up to three other units to provide three-dimensional positional information. A sub-system has an opto-mechanical laser beam stearing mechanism which is electronically controlled and is linked to a general purpose micro-computer. Each sub-system can track at high speed the position of an optically passive retroreflective target, attached to the robot arm, by aiming a beam of collimated coherent light at its optical centre. The result is a line-of-sight along which the target is known to lie but which does not inherently provide range information. Figure 1 illustrates the use of a single sub-system to collect information from movements which are constrained to a defined surface, generally a plane perpendicular to the line-of-sight. Possible applications of a single unit could include modal analysis where the presence of defects in the robot structure or controller are identified through monitoring the arm response to white noise input commands and analysing the arm movement data using coherence techniques. [11]

Figure 2 shows a more general arrangement which aims at measuring the x, y, z position co-ordinates of the robot end effector. The addition of a second sub-system which tracks the same point as the first sub-system provides a further line of sight definition that can be used to provide range information through a triangulation calculation that results in an absolute measurement. An interruption of one or both beams only requires the re-establishment of tracking without loss of calibration. With the present equipment this requires approximately 1 ms to implement. A superfluous 4th datum is available and is used to assess the quality of the triangulation calculation. The tracking instrument and data collection are controlled by a micro-computer which has interactive graphics to provide the results of the calculation in an understandable format. Mass storage units, such as a tape streamer, a flexible disk drive and a hard disk are also available for data storage so that data averaging, filtering, and so on may be carried out on several tests.

For certain applications it might be necessary to provide not only information about the end effector's position but also about its orientation. For this purpose two more sub-systems are used. Two configurations can be adopted. One configuration consists of using two sub-system pairs, with each pair monitoring the co-ordinates of one target of a pair. This provides 5 degrees of freedom i.e. x, y, z and horizontal and vertical angles of the target pair using a linear calculation. The other configuration consists of each sub-system monitoring one target of a cluster of four. A non-linear calculation results in a measure of all 6 degrees of freedom of the robot end effector.

3. System Calibration

The instrument can only provide high accuracy and repeatability if the various constituent components of the system are modelled and calibrated. This must be performed at three levels; at the individual measuring component level, at the sub-system level, and at test site level. Of these, the sub-system is the most complex and will be considered first. Figure 3 shows the optical components of a sub-system which consist of a linearly polarised laser, a quarter-wave plate to optically isolate it, and a collimator to expand it to a convenient diameter. To deflect the transmitted beam to the target, there are two orthogonal plane mirrors attached to moving-iron galvanometer scanners. The reflected beam from the

optical target returns parallel to the transmitted beam to impinge on the photodiode quadrant detector. The deflection of this beam from the centre of the detector is a measure of the tracking error which is used to drive the scanners to reduce this error in a closed control loop.

To calibrate a sub-system requires the calculation of the line-of-sight equation to the target based on the knowledge of the two scanning mirror angular positions as well as the lateral distance between the outgoing laser beam and target centre point. These numerical values are used with a geometric model of the sub-system. The model accounts for any possible departure of the real tracking head from the nominal design dimensions and is in parametric form. This makes it suitable for least square optimisation, in the case of dimensions not easily measured using direct methods.

The basic system components, such as the scanner transducer and quadrant detector photocell, are calibrated individually under conditions reflecting their actual use to accuracies in excess of that expected for the system components.

The determination of the relative position and orientation of the two sub-systems at a test site uses an indirect method. It involves, prior to performing actual tests, the measurement of two targets attached to a calibrated bar as well as the measurement of a set of random and unknown 3D positions. All six degrees of freedom are determined this way. The bar is made of carbonfibre which has a temperature expansion coefficient of $-0.7 \times 10^{-6}/°C$, thus providing good position stability.

In addition, the overall measurement uncertainty due to basic component errors has been assessed on the assumption that the sub-system and site calibration have been adequately performed. As triangulation involves an angular measurement, any angular error of the scanner system is crucial. Figure 4 shows the contribution of the scanner angular position measurement error to the measurement uncertainty based on 1 arc sec of scanner error with the sub-systems separated by 1 metre. Uncertainties are calculated in metres and increase linearly with separation distance and scanner error.

Overall calibration of the present system reveals a repeatability of better than ± 0.1mm in x, y, z directions for one standard deviation based on 30 tests. The tests were repeated at twenty nominal positions along a straight-line precision slideway equipped with a linear optical encoder. The total distance between the positions was 0.8m.

4. Some instrument results

Figure 5 shows the results produced by the laser measuring instrument for the accuracy and repeatability testing of an industrial robot. The test consists of a cycle of 5 points, repeated 30 times. These results are for one of the points. All data is referred to the robot reference frame to ease its interpretation. Numerical data is also provided with information on the statistical spread of the repeated positioning as well as the cartesian difference between the demand and mean attained positions. Figure 6 shows the results of a trajectory test where the robot must describe a rectangular path three times. The measured trajectory is projected on to the three cartesian planes of the robot reference frame. Figure 7 shows the results for the same dynamic test but as a function of time.

Typically for a measurement volume of 1 m^3 the measurement is currently achieving tracking speeds in excess of 3 m/sec with a measurement accuracy of 0.5 mm and a repeatability of ± 0.1 mm. The repeatability is reduced to 20 μm for a stationary target by taking the mean of 30 readings at a sampling rate of 200 Hz. The target can be tracked from 0.5 to 6 metres away from the sub-systems in the laboratory giving a variable measurement volume of approximately 0.01 to 27 m^3. The rangeability (the measurement range/resolution) is typically 10,000:1. Current work shows that improving rangeability by a factor of 5 can be achieved if required.

5. Potential space-station applications for laser triangulation

5.1 General

The permanently manned Space Station project being developed by NASA, with the participation of Canada, Europe and Japan, provides a unique opportunity to develop a wide range of automatic and robotic concepts in space. This should improve productivity, reliability, safety and give greater system flexibility. As far as the U.K. is concerned, the Department of Trade and Industry is sponsoring an Advanced Robotics Initiative in Space Applications as part of the European Programme. A proposal is being considered for the development of an Internal Experiment Manipulator (IEM) as a space laboratory work-cell demonstrator by a consortium headed by Logica.

The development of robots in space will initially use tele-operation under direct astronaut control with force reflected master-slave control. These systems will be capable of performing such tasks as removing and installing fasteners and umbilical cords, routine maintenance, space station construction and so on. The NASA/Johnson Space Center approach using the Shuttle Remote Manipulator System for Space Station assembly is a good illustration of tele-operated robot development.

As robots develop further there will be an evolutionary change towards autonomous robots. A range of sophisticated sensors will provide the robot with environmental and task information while the astronaut acting as a supervisor defines the task, monitors the robot and resumes control after the task is completed. Part of the NASA program foresees a Space Station Mobile Remote Manipulator System which can undertake autonomously Station assembly, Station/satellite maintenance and repair, and routine inspection.

Most of the external tasks required for robotic operations at the Space Station may be grouped under the headings of assembly of space structures, maintenance and repair, inspection. In addition, there will be internal tasks as the Space Station will support a variety of laboratories operating under microgravity conditions. Many of these laboratories will use low-reaction robots [12] operating at relatively high speed in an ordered environment not unlike industrial situations on earth.

All these tasks will require a wide variety of sensory information in which vision techniques will be predominant [13], particularly as robots become more autonomous. However, there is an important requirement for a range of non-contact position measurement and control which may be met optically without recourse to the complexity of full vision information processing. Thus

applications such as docking, automatic and manual steering of remote manipulators, robot calibration in space laboratories are very suitable for laser tracking and triangulation technology. This approach provides absolute measurement, is robust from a control point of view, has a wide range of static and dynamic characteristics and has acceptable accuracy. Some indications of the approach to be used in these application areas are now considered.

5.2 Docking

Krishen [13] provides information on laser docking system performance goals (Table 1) and suggests that in docking and berthing applications a robotic vision/sensing system may be needed within a cone of 30 deg. to a distance of 50 m. Beyond this zone it is envisaged that a radar system may be used for tracking and monitoring the object motion. From the work on the laser tracking system described in Sections 2 to 4 the range and range rate accuracy requirements are well within the capability of the present electro-optic technology. The angular resolution requirements for bearing and attitude are also not very stringent but the angular rate resolution of 0.002 deg/s is quite demanding but achievable. Depending on the complexity of the docking configuration, a 2 or 4 laser beam configuration would provide all the measurement information required and could probably work satisfactorily at distances further away than 50 m.

5.3 Automatic and manual steering of remote manipulators

Despite astronaut tele-operator control of remote manipulators at the present time, there is probably scope for improvements in the speed and accuracy of task performance. This is mainly due to the complexity and flexibility of the manipulator arm structures used together with the range of loads carried by the arms. Improvements can be made to the arm dynamics by detailed mathematical modelling of its characteristics and the use of complex control laws. However, a more straightforward approach is possible by the direct positional control of the end-effector using on-line laser tracking and triangulation. The static and dynamic characteristics are well within the capability of such systems (see Section 4) and on-line control at the trajectory velocities required can be implemented with conventional microprocessor technology. Some consideration would need to be given to determine the optimal control strategy for each joint to follow the overall position demand. For tele-operator control of the position loop the demand information would be generated directly from the joy-stick.

5.4 Robot calibration in space laboratories

It is envisaged that a robot arm might have to move between several work-cells within a laboratory as well as the manipulation tasks within each cell. Many experiments will require a very high degree of isolation from reactive forces generated by the robot, Space Station, etc. thus requiring correction between the manipulator's reference co-ordinate frame and that of the work-cell. Ideally the calibration sensor system should be based on the work-cell so that it measures the position of the manipulator end-effector relative to the experiment. The advantage of this method is that it compensates for any possible errors in the robot structure and controller together with any relative movement between the robot and experiment base plants. Again, for the distances and accuracies involved, triangulation devices can be in-built to each work-cell to provide on-line calibration.

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6. Conclusions

An industrial laser tracking instrument working on triangulation principles has been described together with some of its characteristics. It can provide absolute positional and orientation information, its rangeability is good, it has robust tracking control and has the necessary resolution to meet a significant number of space sensory and control requirements. A number of applications have been discussed where static and dynamic metrology can compliment the more sophisticated vision sensing developments required for space tasks.

Acknowledgements

References

1. Warnecke, J.J. and Brodbeck, B., "Test Stand for Industrial Robots", 7th International Symposium on Industrial Robots, Tokyo (Japan), Oct 1977, pp. 443-451 .

2. McEntyre, R.H., "Three Dimension Accuracy Measurement Methods for Robots", The Industrial Robot, September 1976, pp. 105-112 .

3. Desmaret, J.P., "Methods de mesures tridimensionnelles a l'aide de deux theodolites", Direction des Techniques Avancees en Automatisme, Groupe Mesure, October 1981.

4. Fohanno, T., "Assessment of the Mechanical Performance of Industrial Robots", 12th International Symposium on Industrial Robots, 1982, pp. 349-358.

5. Selspot II - a complete system for sophisticated motion analysis, Sweden, SELCOM AB, Box 250, S433 25, Partille.

6. CODA 3 Movement Monitoring System, Movement Techniques Ltd., Unit 5, The Technology Centre, Epinal Way, Loughborough, Leicestershire, LE11 OQE, England.

7. 3-Dimensional Sonic Digitiser, Model GP-8-3D, Science Accessories Corporation SAC, 970 Kings Highway West, Connecticut 06490, USA.

8. Burton, R.P. and Sutherland I.E., "Twinkle Box - A Three dimensional computer input device", National Computer Conference, AFIPS Press, 1974, pp. 513-520.

9. Gilby, J.H. and Parker, G.A., "Robot Arm Position Measurement Using Laser Tracking Techniques", 7th Annual British Robot Association Conference, 1984.

10. Lau, K.; Hocken, R. and Haight, W., "An automatic laser tracking interferometer system for robot metrology", 3rd Int. Precision Engineering Seminar, Interlaken, Switzerland, May 1985, pp. 100-102.

11. Dagalakis, N.G., "Analysis of Robot Performance Operation", 13th International Symposium on Industrial Robots, 1983, pp. 7-73 to 7-95.

12. Rohn, D.A.; Lawrence, C. and Brush, A.S., "Microgravity robotics technology programme", ISA 88, Houston, U.S.A., October 1988, Paper 88-1642.

13. Krishen, K., "Space Robotic Vision System Technology", ISA 88, Houston, U.S.A., October 1988, Paper 88-1615.

PARAMETER	LIMITS	ACCURACY (σ)
Range (R)	0-1 km (3280 ft)	.01 R; 2.5 mm ≤ 10 m
Range Rate	±3 m/s (±10 ft/s)	.0001 R/s; 3 mm/s ≤ 30 m
Pointing	±π/2 rad (±90°)	
Bearing Angle	± .2 rad (±10°)	3 mrad (.2°)
Bearing Angle Rate	±20 mrad/s (±1°/s)	.03 mrad/s (.002°/s)
Attitude (P.Y)	± .5 rad (±28°)	7 mrad (.3°) ⎫
Attitude (R)	±π rad (±180°)	7 mrad (.3°) ⎬ at R≤100 ft
Attitude Rate	±20 mrad/s (±1°/s)	.03 mrad/s (.002°/s) ⎭
R, $\dot{R}$ Output Data Rate	1 Hz	
Angle Output Data Rate	3.125 Hz	

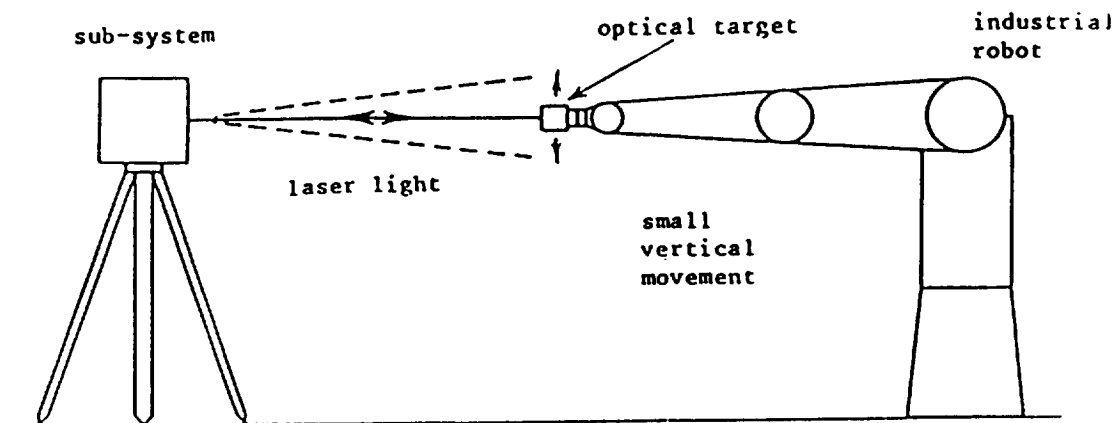**Table 1: Laser Docking System Specification**
(Ref 13)

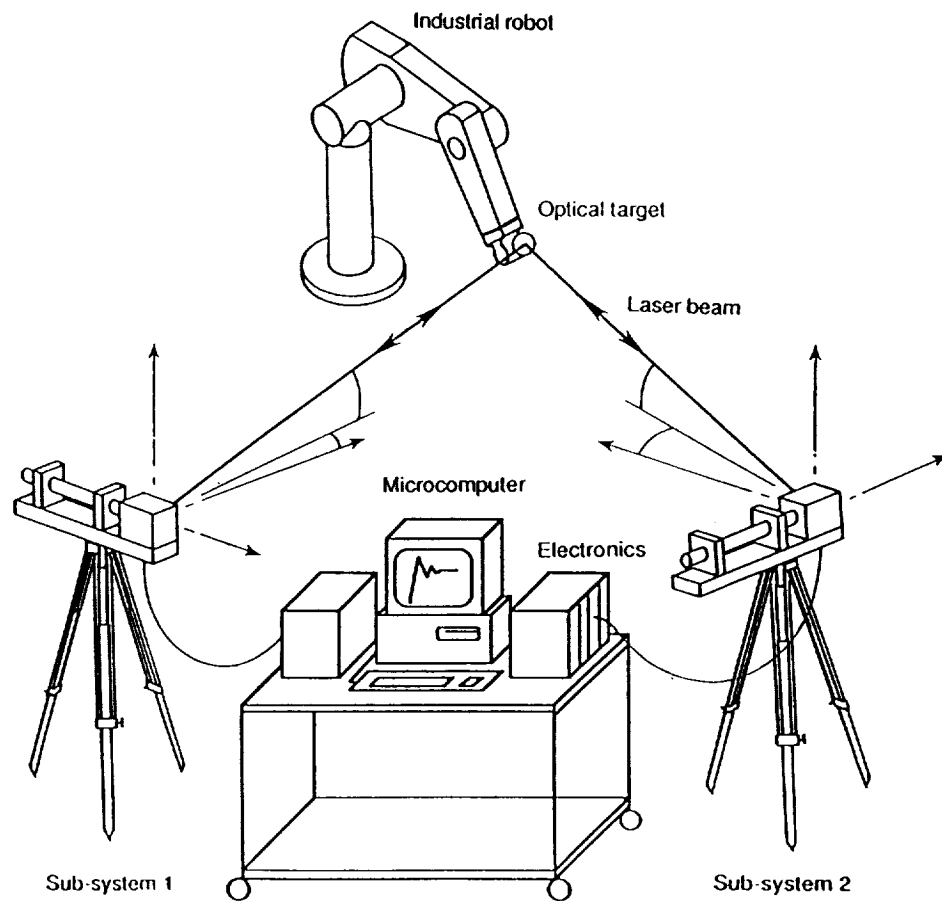Figure 1 - Use of a single sub-system for measurements in a plane

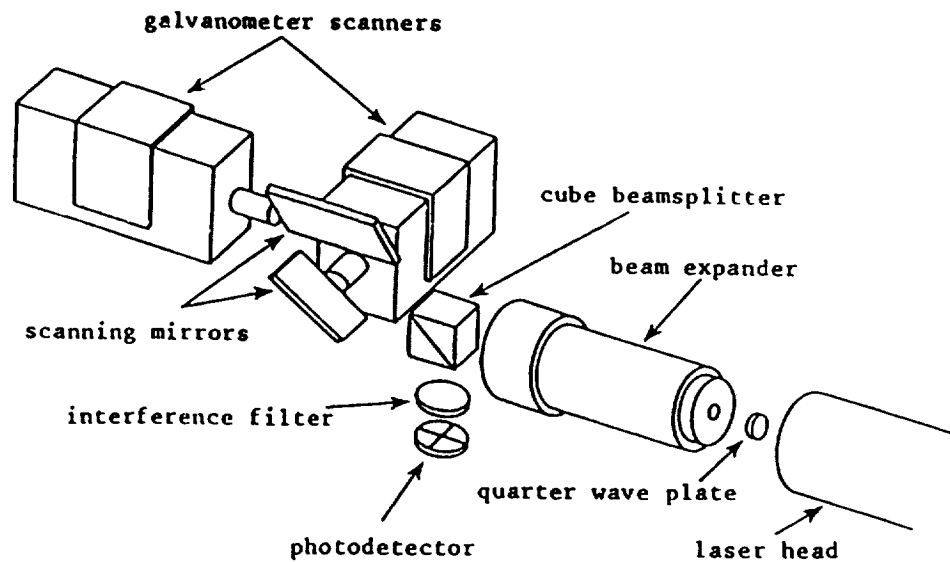Figure 2   Diagram of the Laser Tracking Triangulation Method

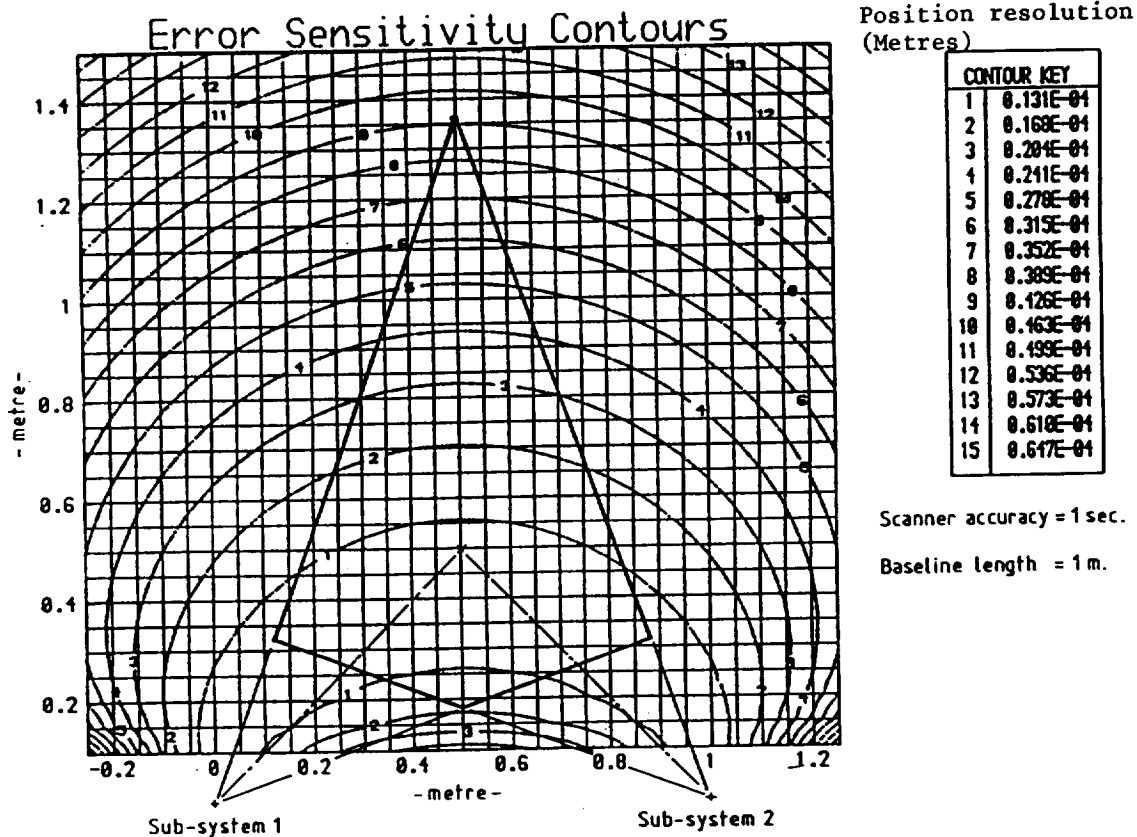Figure 3 - The Optical Hardware of a Sub-System

Error Sensitivity Contours

Position resolution
(Metres)

CONTOUR KEY	
1	0.131E-01
2	0.168E-01
3	0.204E-01
4	0.241E-01
5	0.278E-01
6	0.315E-01
7	0.352E-01
8	0.389E-01
9	0.426E-01
10	0.463E-01
11	0.499E-01
12	0.536E-01
13	0.573E-01
14	0.610E-01
15	0.647E-01

Scanner accuracy = 1 sec.

Baseline length = 1 m.

Sub-system 1   Sub-system 2

Figure 4   Effect of scanner angular uncertainty on the final co-ordinate
           measurements

Data file name: T09P3.DIS
Number of points: 30
Command pose (m): (0.47911, 0.08018, 0.75722)
            (deg): (0.0, 0.0, 0.0)
Mean attained pose (m): (0.47919, 0.08013, 0.75714)
Accuracy:
 -ISO: 128 μm
 -Cartesian (μm): (89.9, -53.8, -73.5)
Repeatability:
 -ISO R: 77 μm
 -Cartesian (3sx,3sy,3sz) (μm):(79.3, 50.3, 45.3)

(c) 1988 Robotics and Optical Metrology Laboratory,
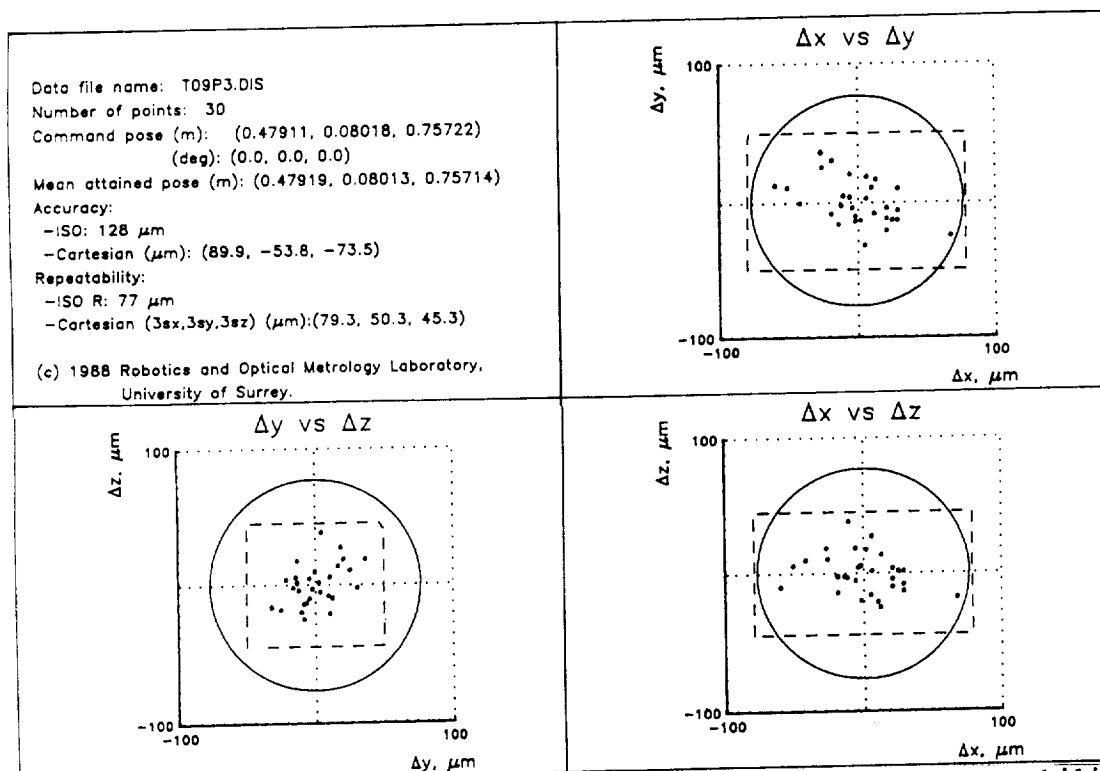   University of Surrey.

Figure 5   Representation of the results of a static accuracy & repeatability test
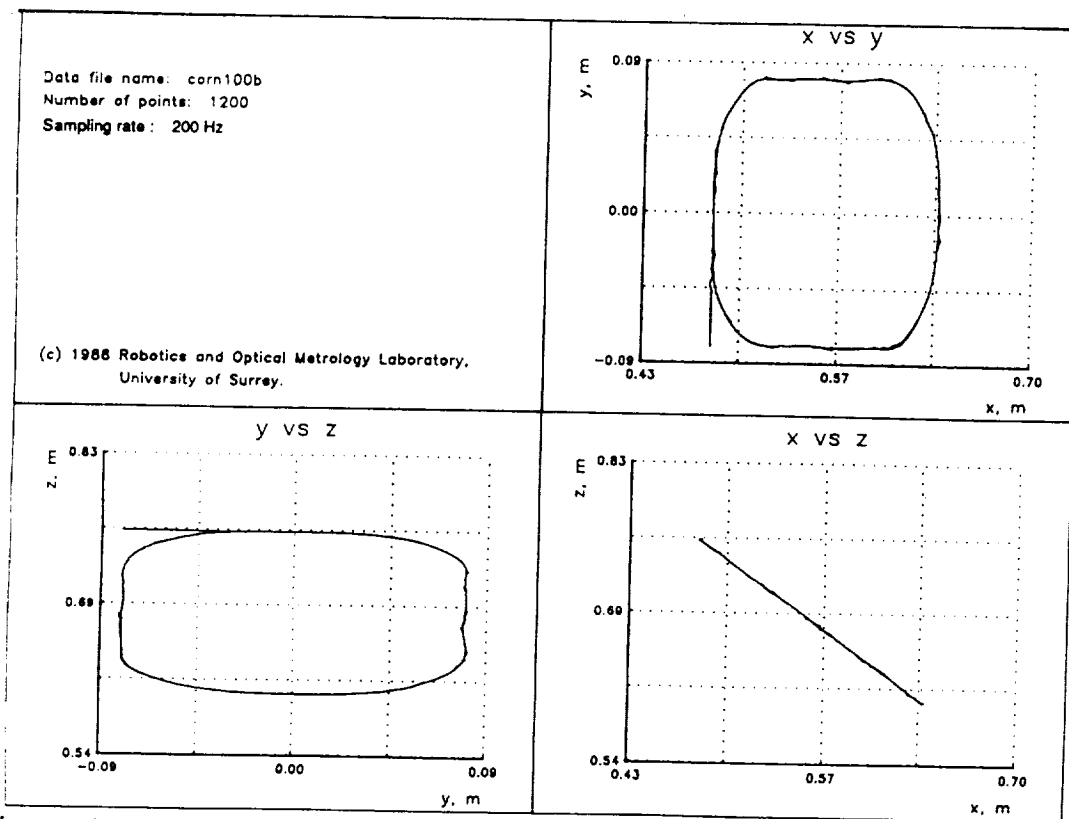
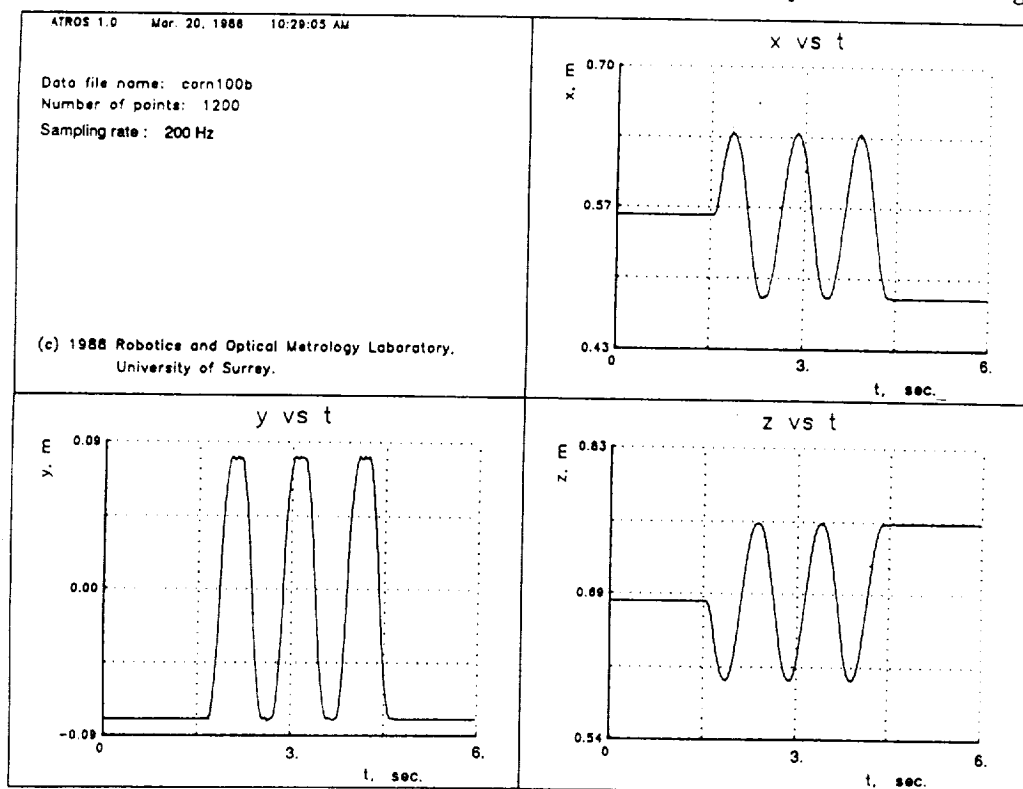**Figure 6** Spatial representation of the results of a dynamic cornering test

Figure 7 Temporal representation of the results of a dynamic cornering test